WOPPER, Version 1.1: A Monte Carlo Event Generator for Four Fermion Production at LEP-II and Beyond[*][†]

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We report on the status of the Monte Carlo event generator WOPPER. Version 1.1 of WOPPER describes four fermion production at LEP-II and beyond with leading logarithmic radiative corrections in the double $W^{\pm}$ pole approximation. These approximations are appropriate for almost all practical purposes, but the inclusion of these finite width effects and radiative corrections is nevertheless indispensable for LEP-II physics.

1. Introduction

The Monte Carlo event generator WOPPER [1] for four fermion production through $W^{\pm}$ resonances at LEP-II and beyond is the latest addition to the Darmstadt/Siegen family of Monte Carlo event generators [2]. It is a true event generator that generates a sample of unweighted events which can be used directly in detector simulations for experiments at LEP-II and future linear e^+e^- colliders [3]. The distinguishing features of WOPPER are: off-shell pair production in the double pole approximation and resummation of the leading logarithmic (initial state) radiative corrections.

2. Requirements

While we still need to add a direct observation of the triple gauge vertices (TGV) to the overwhelming indirect evidence for their existence, any potential deviation from the standard model values will in all likelihood be very small [4].

Thus an observation of these small anomalous couplings in the permille range will only be possible at an high luminosity collider beyond LEP-II, if all standard model corrections are know to an even better precision. This is only possible if several independent semi-analytical and Monte Carlo programs are available, which include (and agree on) all important contributions.

In the nearer future, the prime physics objective of LEP-II will be a precise measurement of the $W^{\pm}$ mass, which will provide an important cross check of the standard model and help to constrain possible physics beyond. For example, reducing the error below 100MeV could close the window for light Higgses (and therefore the minimal supersymmetric standard model) using constraints from the electroweak radiative correction parameter Δr, as reported at this conference [5]. Proper accounting for finite width effects and radiative corrections is of crucial importance for this measurement. This calls for reliable calculations and Monte Carlo event generators.

3. Features of WOPPER

3.1. Radiative Corrections

WOPPER concentrates on the gauge invariant subset of radiative corrections which is phe-

nomenologically most important. The leading logarithmic $(\alpha^n \ln^n(s/m_e^2))$ radiative corrections from the initial state leptons are resummed to all orders, including the exponentiation of soft photons.

Because of the t-channel ν-exchange diagram, it is not possible to unambiguously separate the complete $\mathcal{O}(\alpha)$ initial state radiative corrections in a gauge invariant way. The restriction to the leading logarithmic contribution is therefore phenomenologically reasonable and theoretically sound.

While the resummation of terms beyond $\mathcal{O}(\alpha^2)$ is numerically irrelevant for the projected LEP-II statistics, the fully resummed form can be obtained at no extra cost in a Monte Carlo event generator and has the desirable side effect of an unproblematic probabilistic interpretation. All finite order approximations suffer from the so called k_0 problem: for some infrared cut k_0 on the emitted photon energy, the cross section

$$\sigma \approx \left(1 - \mathcal{O}(1) \cdot \frac{\alpha}{\pi} \ln \frac{s}{m_e^2} \ln \frac{E_{\text{Beam}}}{k_0}\right) \cdot \sigma_0 \qquad (1)$$

in the channel with no emission of a photon becomes negative. In the resummed form, however, the big negative term in (1) exponentiates and leads to a small but positive cross section. Therefore the generated event samples are physically meaningful and the corresponding cross sections do not depend on the soft photon cut introduced by the experimental resolution.

Besides the theoretical advantage of keeping only the gauge invariant leading logs, these corrections have the benefit of leading to a factorized cross section. Denoting the phase space variables under consideration collectively by [PS], the cross section reads

$$\frac{d\sigma_{LLA}}{d[\text{PS}]}([\text{PS}])$$

$$= \int_0^1 dx_+ dx_- D(x_+; \mu^2) D(x_-; \mu^2) \qquad (2)$$

$$\times \frac{d\sigma_0}{d[\text{PS}']}([\text{PS}']) \frac{\partial[\text{PS}']}{\partial[\text{PS}]}$$

where the [PS'] depend on [PS], and the energy fractions $x^\pm$ of the initial state leptons. For example, we have $s' = x^+ x^- s$ for the center of mass
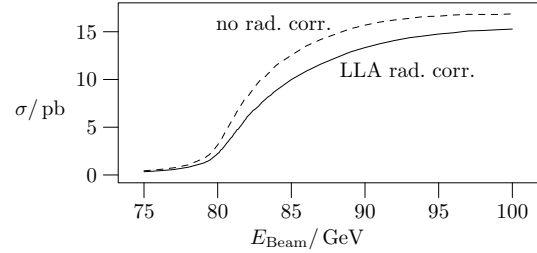

Figure 1. Effect of radiative corrections on the total cross section near threshold.

energy squared. This cross section can be implemented easily in an event generator. Here the electron distribution functions $D(x; \mu^2)$ obey the DGLAP renormalization group equation:

$$\mu^2 \frac{\partial D(x; \mu^2)}{\partial \mu^2} \qquad (3)$$

$$= \frac{\alpha}{2\pi} \int_x^1 \frac{dz}{z} \left[\frac{1+z^2}{1-z}\right]_+ D\left(\frac{x}{z}; \mu^2\right)$$

From the cross section (2) it can be seen that the important effects are either universal or of a simple kinematical origin: the shape of the total cross section will be shifted towards higher energies because of the energy loss from radiated photons ("radiative tail", cf. figure 1). Particles which would be back-to-back due to momentum conservation in non-radiative events will be acollinear in radiative events.

The Monte Carlo implementation of (2) in WOPPER first solves a suitably infrared regularized version of (3) with a universal photon shower Monte Carlo and use the sample corresponding to this solution to define an effective center of mass system (CMS) for each event after radiation of initial state photons. In this new CMS a relatively simple Born type $e^+e^- \to 4f$ event can be generated, which will then be boosted back to the laboratory frame. This final boost incorporates all kinematical effects, like acollinearities for the intermediate W's, etc.

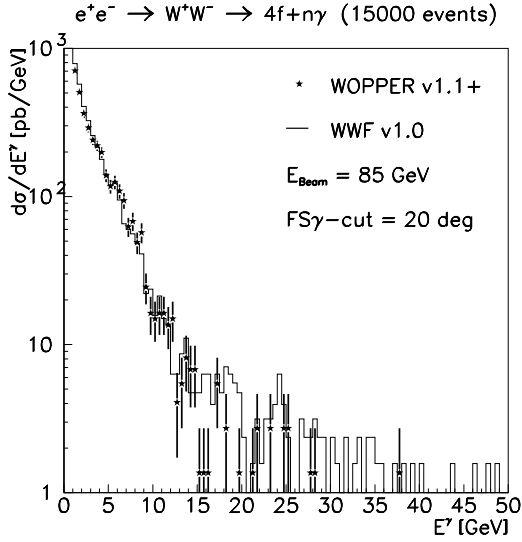While this approach is more than adequate for all inclusive distributions, there remain two areas

Figure 2. E^γ spectrum at $\sqrt{s} = 170\,\text{GeV}$, comparing `WOPPER`'s LLA prediction with `wwf`'s $\mathcal{O}(\alpha)$ prediction. An angular cut for photons around any charged particle in the final state has been applied.

Figure 3. Same as figure 2, but for the photonic transversal momentum p_T^γ.

where further progress is needed: large photonic p_T^γ and final state radiation.

By its very definition, the leading logarithmic or pole approximation is applicable to collinear radiation and inclusive spectra because these are dominated by collinear radiation (cf. fig. 2, where the LLA is compared to a $\mathcal{O}(\alpha)$ calculation). But for large photonic p_T^γ the LLA is essentially an uncontrolled approximation. However, we can use existing $\mathcal{O}(\alpha)$ Monte Carlos [6] to gauge the numerical accuracy of the LLA even for large p_T^γ. It turns out that the pole approximation reproduces the full $\mathcal{O}(\alpha)$ calculation surprisingly well in the projected LEP-II energy regime (cf. fig. 3). At 500GeV on the other hand, the large p_T^γ region is overestimated (cf. fig. 4).

The other problematic issue concerns final state radiation. While the figures 2, 3 and 4 confirm that a reasonable angular cut around any charged particle in the final state will remove all effects of final state radiation, are more complete Monte
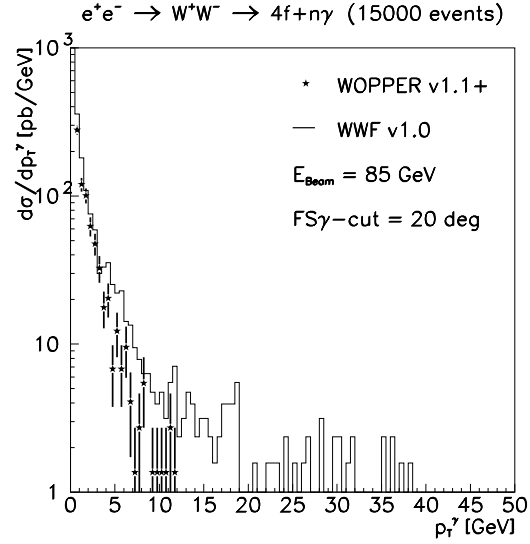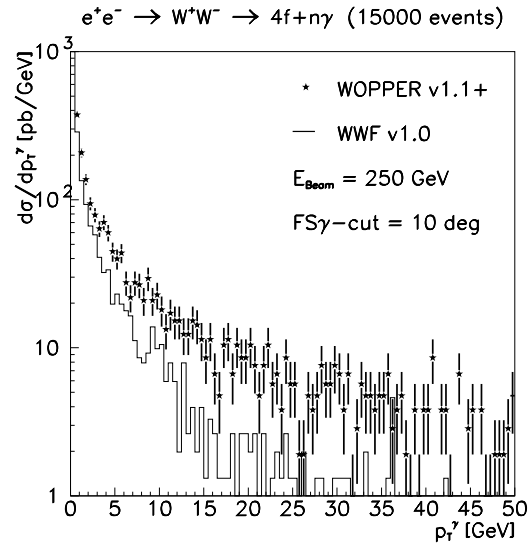
Figure 4. Same as figure 3, but at higher energy $\sqrt{s} = 500\,\text{GeV}$.

Carlo treatment is of course desirable.

3.2. Finite Width

For detailed background studies, it is of course necessary to study all non-resonant diagrams contributing to $e^+e^- \rightarrow 4f$ at LEP-II energies [7]. For the identification of W^+W^- pairs, experimental invariant mass cuts will have to be applied, however. After such cuts, the contribution of non-resonant diagrams goes down rapidly [7].

For the sake of efficiency, version 1.1 of `WOPPER` implements the four fermion final states therefore in double pole approximation. This is equivalent to keeping the two so-called "signal" diagrams.

For all practical purposes, the $W^\pm$'s decay into light quarks only (b's are still relatively light and because of the small $|V_{cb}|^2$ rare). Thus the unphysical polarizations decouple and the cross section factorizes

$$
\begin{aligned}
&\sigma_{\text{resonant}} \\
&= \int ds_+ ds_- \frac{\sqrt{s_+}\,\Gamma_W(s_+)}{\pi D(s_+)} \frac{\sqrt{s_-}\,\Gamma_W(s_-)}{\pi D(s_-)} \quad (4)\\
&\quad \times \sigma_{\text{off-shell}}(s; s_+, s_-)
\end{aligned}
$$

into "off-shell" production $\sigma_{\text{off-shell}}(s; s_+, s_-)$, Breit-Wigner propagators

$$
\frac{1}{D(s_\pm)} = \frac{1}{(s_\pm - M_W^2)^2 + s_\pm \Gamma_W^2(s_\pm)} \,. \quad (5)
$$

and decay widths $\Gamma_W(s_\pm)$. This factorized form is again very convenient for implementation in a Monte Carlo event generator. The resulting cross section, displaying the typical smearing of the threshold, is depicted in figure 5.

3.3. Parton Showers, Fragmentation and Hadronization

The description of semileptonic and hadronic W^+W^- events is of course incomplete without proper accounting for the hadronization of the quarks in the final state. Working interfaces of `WOPPER` to both major final state parton shower and fragmentation models `JETSET 7.4` [8] and `HERWIG 5.5` [9] are implemented as of version 1.1. Therefore the events generated by `WOPPER` can be fed immediately to detector simulation Monte Carlos.
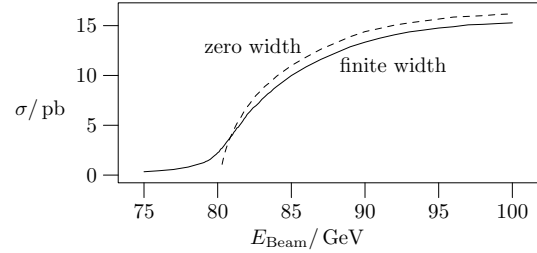

Figure 5. Effect of the finite $W^\pm$ width on the total cross section near threshold.

4. Sample Application

At high energies, the transversally polarized $W^\pm$'s from the t-channel diagram are dominating the cross section. From a physics perspective however, the longitudinally polarized $W^\pm$'s and the contribution from the s-channel diagram are both far more interesting. The former because the longitudinal $W^\pm$'s are a direct manifestation of electroweak symmetry breaking and the latter is where the three gauge boson vertex is to be measured.

It is therefore important to be able to reconstruct a sample of longitudinally polarized $W^\pm$'s. Fortunately, the $V - A$ decay of $W^\pm \rightarrow f\bar{f}'$ is self analyzing, if we can measure the angular *decay* distribution:

$$
\sigma_{+,0,-} = \int d\cos\theta^* \, P_{+,0,-}(\cos\theta^*) \frac{d\sigma}{d\cos\theta^*} \quad (6)
$$

Here the $P_{+,0,-}$ are simple polynomials [10].

In the case of on-shell $W^\pm$'s without radiative corrections, the decay angle can be reconstructed in semileptonic decays by measuring the energy E_ℓ of the charged lepton only [10]

$$
\cos\theta^* = \frac{2E_\ell - E_B}{\sqrt{E_B^2 - M_W^2}}. \quad (7)
$$

However, using semi realistic acceptance cuts of $175° > \theta > 5°$, this method fails in the presence of finite $W^\pm$ width and radiative corrections, as can be seen from the fat histograms in figures 6 and 7.

On the other hand, it seems to be more promising to try to reconstruct the neutrino momen-
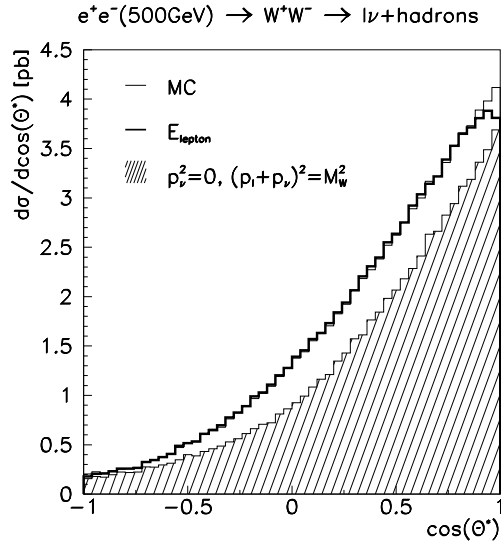
Figure 6. Different methods of reconstructing the decay angle θ^* in the presence of acceptance cuts ($175° > \theta > 5°$) and finite $W^{\pm}$ width.
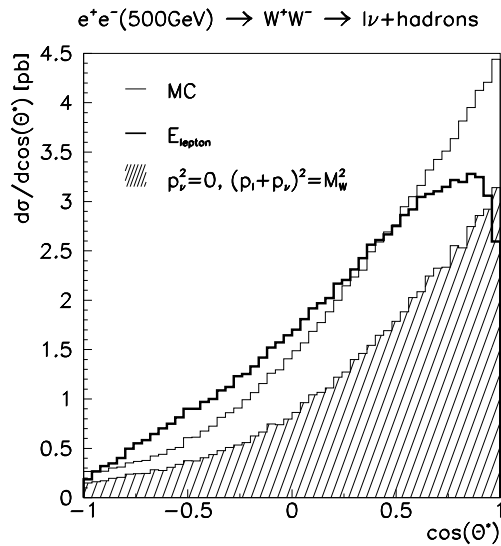

Figure 7. Same as figure 6, but additionally including leading log initial state radiative corrections.

tum from the missing transversal momentum, the mass shell condition $p_\nu^2 = 0$ of the neutrino and the approximate mass shell condition of the leptonically decaying W: $(p_\ell + p_{\nu_\ell})^2 = M_W^2$. If we add the further requirement that the squared sum of all reconstructed momenta should deviate no more than 10% from the squared CMS energy, we get the much improved hashed histograms in figures 6 and 7. They are in particular free from the characteristic shape distortions generated by the first method.

5. Conclusions and outlook

WOPPER is a fast, flexible and supported tool for $W^{\pm}$ physics at LEP-II and beyond. Comparisons with other Monte Carlos [6] has shown that the approximations used in WOPPER (leading log radiation, resonant W's) can easily be controlled for experimentally relevant cuts. In the forthcoming releases, the following features will be added:

- Anomalous couplings. This feature has been requested by experimentalists during this workshop again. Therefore this straightforward, if somewhat tedious, enhancement will be installed.

- Non electromagnetic radiative corrections. We will add the dominant contributions which go beyond the running QED coupling. The latter is of course already available.

- Coulomb singularity. We will add this feature soon, again by popular demand[8]. For the time being, it will implemented inclusively, without generation of the corresponding soft photons.

- Improved photonic p_T^γ spectrum. Comparison with complete $\mathcal{O}(\alpha)$ Monte Carlos shows that the LLA is an excellent approximation for inclusive distributions and longitudinal spectra. There remains however a noticeable discrepancy at high photonic p_T^γ,

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[8]At the time this contribution to the proceedings is written, the Coulomb singularity has already been implemented in WOPPER, Version 1.2.

which can not be described in LLA. This situation will be improved, either by explicit inclusion of non leading terms or by phenomenological interpolation.

- Final state radiation and interference terms. This will come somewhere further down the road.

Due to the slowly varying nature of the $e^+e^- \to W^+W^-$ cross section, the forward branching algorithm [2] with hand crafted importance sampling as implemented in WOPPER v1.x is sufficient for most practical purposes. We shall however replace it by a backward branching algorithm, which will blend better with a general purpose Monte Carlo engine, where the cross sections can be replaced more easily [11].

6. Distribution policy

WOPPER is distributed electronically over the Internet using the following channels:

- The FORTRAN-77 sources (in PATCHY format) can be obtained by anonymous Internet ftp from the host crunch.ikp.physik .th-darmstadt.de in the directories pub /ohl/wopper/old, pub/ohl/wopper/pro and pub/ohl/wopper/new, corresponding to slightly outdated, current and experimental releases of WOPPER respectively.

- The current status of WOPPER can be queried through the World Wide Web from the document http://crunch.ikp.physik.th -darmstadt.de/monte-carlos.html.

- Important announcements (new versions, fatal bugs, etc.) will be made through the mailing list wopper-announce@crunch. ikp.physik.th-darmstadt.de. Subscriptions should be mailed to wopper-announce -request at the same host. The purpose of wopper-announce is not general discussions of WOPPER, however, if there is interest among users, a companion list wopper -discuss can be created by the authors easily.

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